FATIGUE OF ALUMINUM AS AFFECTED BY TEMPERATURE AND INTERMITTENT PERIODS OF REST

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TEM – TEMPERATURE

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ABSTRACT

This investigation was undertaken in an attempt to determine the behavior of high purity aluminum when subjected to fatigue stressing in rotary bending at various elevated temperatures, and also to study the effects on fatigue life when the material was given intermittent periods of rest. Two types of rest periods were given; 1) room temperature resting from fatigue cycling at elevated temperature, and 2) resting at higher temperature after stressing at ambient temperature. Because of the limited time available and the desire to apply statistical methods of analysis, testing was restricted to only a single stress level for each phase of the experiment.

Up to the highest temperature tested (600°F), results for continuous stress cycling indicate a gradual reduction in fatigue life with temperature. Rest periods at room temperature contributed only negligible changes in fatigue life, but all tests with rest periods at elevated temperature disclosed a sizable increase. The increase in fatigue life was a maximum when resting was carried out at temperatures in the neighborhood of the recrystallization temperature. In addition, it is curious to note, that in the continuous cycling tests, scatter of results was a sharp minimum at recrystallization temperature.

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I. INTRODUCTION

Relatively little work has been done in regard to fatigue endurance as influenced by rest periods. Perhaps the most notable contributor has been Freudenthal. In reference 1, Freudenthal shows that intermittent rest periods at elevated temperature below recrystallization temperature increased the fatigue life of SAE 4340 and SAE 1045 steel specimens, while they reduced the fatigue life of copper specimens. It was also reported, but not confirmed, that other workers had shown that for aluminum a decrease in fatigue life would be the result of periods of rest.

In reference 2, Cazaud cites the work of Moore and Putnam to show that momentary cessation of fatigue stressing has no beneficial effect on fatigue strength as long as the applied stress is less than the elastic limit. Apparently, if the stresses exceed the elastic limit, a slight increase in fatigue strength may be observed. He also cites others to show that in soft iron and carbon steels, improvement in life may be expected due to periods of rest; the effect being greater for longer rest periods and also greater at higher temperatures of rest.

In the course of a continuing research program at the Guggenheim Aeronautical Laboratory; Valluri, from tests on commercially pure aluminum, proposes the existence of a critical temperature at which the fatigue life in torsional cycling becomes a minimum compared to life at temperatures in the near vicinity. In reference 3, he reports the effect of this critical temperature on internal friction at various stress levels as quite substantial; and also that an appreciable change in internal friction was noticed during periods of rest following periods of fatigue stressing. Presumably, this change in internal

friction occurs by a process of relaxation of shear stress across grain boundaries and slip bands; and it is suggested that on a microscopic scale this manifests itself in polygonization followed by the growth of sub-grains during periods of rest. Valluri surmises that this redistribution of internal stresses may provide an increase in fatigue life.

Valluri's results were based on relatively few specimens; and thus, the program of this investigation was designed toward a statistical verification of the above ideas. The investigation is concerned with fatigue stressing in rotary bending of standard R. R. Moore specimens of 99.996 percent aluminum. Temperatures selected for testing were; room temperature, 150°F, 300°F (approximate recrystallization temperature), 450°F, and 600°F.

II. DESCRIPTION OF SPECIMENS AND TEST EQUIPMENT

1. Test Material and Specimens.

The test stock was obtained in the form of one-half inch diameter rolled rods, 12 feet long. The material was 99.996 percent aluminum with .001 percent silicon and .003 percent zinc. There was evidence of considerable amounts of prior coldwork in the material. No heat treatment was given the specimens before testing; and since the test temperatures higher than 300°F are above the normal recrystallization temperature for pure aluminum, there is reason to believe that some recrystallization may have taken place during the process of testing a specimen. Since the material was extremely ductile and the chosen stress levels relatively high, it was considered desirable to run a tensile test on the material. The yield point at two-tenths percent offset was determined to be 6,750 psi. Ultimate strength was 9,800 psi.

Standard R. R. Moore test specimens were machined in accordance with the specifications of reference 4, page 30, with $D = 0.30$ inches and $R = 9.875$ inches. The specimens were polished with 240 Emery paper followed by 600 grit Wetordry Tri-M-Ite paper with lard oil. Care was taken to ensure that final scratches were substantially along the axis of the specimen. This procedure provided an average surface finish of 7 μ ; " μ " referring to the surface roughness in microinches. A profilometer, type Q, model 1, manufactured by Physicists Research Company, was used in determining the roughness. Levigated alumina powder was tried for final polishing, but microscopic examination revealed this to be unsatisfactory.

2. Fatigue Testing Machines.

The tests were conducted on eight rotary bending machines of the R. R. Moore type, manufactured by the O. S. Peters Company. Fig. 1 is a photograph of one of the machines. The machines were arranged in two nests of four each as shown by Fig. 2.

All machines were designed for a nominal speed of 10,000 rpm, but had been previously modified to accommodate a speed control reostat. With the speed control feature the machines could be slowed to 2,000 rpm. Initially, the testing was conducted at the design speed; but it soon became apparent that a speed reduction was necessary.

Because of the high plasticity of the material tested, failure of the specimen seldom occurred as a clean break, but more as a relatively slow sagging. The eccentricity resulting from this bending deflection was sufficient to cause the bearing housings to gyrate wildly before the cut-off switch became actuated. In one instance an upper furnace coil was torn loose by the specimen, and in several cases the flexible coupling between the motor and bearing housings was broken. This trouble was completely eliminated for the rest of the tests by operating the machines at 5,000 rpm.

The specimens were loaded by applying weights to a counter-weighted tray, the nominal outer fiber stress being calculated as follows:

$$S = \frac{16LW}{\pi D^3} \text{ psi.}$$

With a minimum diameter, D, of 0.30 inches, and level arm, L = 4.0 inches, this formula gives: S = 775W psi., where W is the applied load in pounds.

3. Furnaces.

Fig. 3 is a design drawing of the furnaces used with the R. R. Moore machines. Fig. 4 is a photograph showing furnaces, in the open and closed positions, mounted on the machines.

The furnaces used in the first part of the tests were as designed by James and Stalk (refs. 5 and 6, respectively). Due to sagging of the upper element and subsequent shorting out, the furnaces were incapable of maintaining either of the two highest test temperatures for any appreciable length of time. This was unacceptable, since in addition to steady temperature the nature of the testing required the elements to sustain considerable thermal shock arising from rapid heating and cooling.

Tophet A wire of 15 - gage was selected for redesign of the coils, with the idea of self support in mind. Lengths of approximately 48 inches were used in each furnace half. The coils were friction wound on a three-quarter inch circular rod and then pressed into an oval shaped spring. They were then hand shaped to conform to the furnace contour, and the ends threaded through diameters of the terminal bolts and silver soldered. As shown by Fig. 5 the new coils presented almost a solid wall of heating surface around the specimen.

Sensing of the furnace temperature was accomplished with a chromel-alumel thermocouple inserted through the upper furnace half. The thermocouple wires (22 gage) were contained in a two hole ceramic insulator which was held in a brass tube by a set screw. This tube was attached to a bracket at the top of the furnace by a spring and nut arrangement as shown in Fig. 3. This combination permitted adjustment of the position of the thermocouple relative to the specimen by simply turning the nut.

4. Furnace Control Units.

Circuitry for one machine and furnace is schematically shown by Fig. 6. When a specimen fails the motor is stopped by the inboard bearing housing falling onto a cut-off switch. This switch was also utilized to stop the power supply to the furnace.

Furnace temperatures were controllable by pyrometers into which the furnace thermocouple voltages were impressed. Only six of the machines were fitted with furnaces. Of the six pyrometers, two were SYM-PLY-TROL's, manufactured by Assembly Products, Inc.; and four were the Series J Gardsman, made by West Instrument Corporation. The ranges of the pyrometers were from zero to 800°F and since the furnace thermocouple actually read air temperature in the furnace it was necessary to install a shunt resistance in each pyrometer to change the scale factor of it's indicator dial.

A ballast resistance was incorporated in each circuit so that power to the furnace would not be completely interrupted when the temperature reached that selected on the pyrometer. The advantages of this were to lessen the magnitude of the temperature fluctuations in the furnace, and to reduce the working of the coils due to rapid temperature changes. The resistances chosen allowed about 20 percent reduction in power to the furnace when the system was coasting.

Powerstats were used in the circuits so that current inputs to the furnaces could be widely varied to establish a large range of steady temperatures. As explained in part III, the controlling features of the pyrometers and ballast resistances were used only for the continuous cycling phase of the tests; whereas the powerstats were used exclusively to control the furnace temperature where rapid heating was required.

III. PROCEDURE

Operation of the furnaces and R. R. Moore machines for continuous stress cycling a specimen consisted simply of preheating the specimen in the machine to the desired temperature and applying the load. The proper powerstat and pyrometer settings would then maintain the test temperature without further attendance until failure occurred. In giving rest periods to the specimens a more rapid heating technique was desirable, and the testing procedure became more involved. For the sake of clarity, therefore, discussions of the various procedural aspects of the investigation are presented separately below.

1. Test Program. (Rest Periods Defined).

The basic test program consisted of determining the fatigue life of the material under continuous cycling at various temperatures, and also to detect any change in life when subjecting the specimens to periods of rest.

The temperatures selected for the continuous cycling phase were; room temperature, 150, 300, 450, and 600°F. A stress level for these tests was chosen so that failure at room temperature would occur at about $2x10^6$ cycles. The nominal outer fiber stress was 6,040 psi. This same stress level was used for specimens given periods of rest at room temperature from cycling at 150, 300, and 450°F. The resting times were given at one-fifth intervals of mean life, as determined from the continuous cycling tests.

In another phase of the testing the specimens were given rest periods at 150, 300, and 450°F after cycling at room temperature. So that an individual test could be carried to completion within a reasonable

amount of time a higher stress level was used for this phase of the tests. This stress level was 6,800 psi. Here the rest periods were given at intervals of one-fifth mean life as determined from continuous cycling under the higher stress at room temperature.

The rest period for resting at room temperature was arbitrarily defined to be of thirty minutes duration; such period to commence from the time the specimen during cooling reached a temperature of about 100°F. For resting at temperature the periods were of similar duration with the timing started from the time the specimen reached the desired temperature. The rest periods so defined were, therefore, exclusive of the heating and cooling times required.

Static calibrations were done to determine the times necessary. The calibrations were carried through several cycles of heating and cooling in order to simulate actual testing of the specimens. Cooling was accomplished with small electric blower fans. As given below, the average times required were:

Temp. °F.	150	300	450	600
Heating Time to Temp., Min.	3	5	8	12
Cooling Time From Temp. to 100°F., Min.	2	9	13	15

2. Test Procedure for Continuous Cycling.

As mentioned earlier the technique for continuous cycling was to start the specimen in the machine, bring it up to temperature, and apply the load. With the proper pyrometer and powerstat settings the specimen was automatically maintained at the correct temperature.

Calibrations to determine the settings were accomplished by placing a thermocouple under the head of a screw at the center of the specimen. The output of the thermocouple was measured by a Leeds and Northrup portable precision potentiometer. The powerstat and pyrometer settings were then adjusted until the desired specimen temperature was attained. Because of space limitations it was not considered feasible to install slip rings and conduct dynamic calibrations.

The specimen temperature oscillated around the desired temperature because of power fluctuations inherent in the pyrometer control system. At all test temperatures this variation averaged only about ± 1 °/o. Times to attain and stabilize at the various temperatures were determined during calibration. These times were of course lessened if the bearings and furnace had been previously heated. From a cold start the time to stabilize at 600°F was about one hour, times to other test temperatures being less.

Because of looseness in the pyrometer setting controls and the effect of furnace thermocouple position on the specimen temperature, new calibrations were made when either of these had been changed.

3. Test Procedure for Applying Rest Periods.

The heating technique described above was unacceptable in giving rest periods, since a more rapid means of bringing the specimen up to temperature was desired. Toward this end the pyrometers were used simply as indicators of the furnace temperatures. This was done by setting the pyrometer selector beyond the range of the expected furnace temperature so that the current to the furnace would never be interrupted. Excessive power was then introduced to the furnace by adjusting

the powerstat until the specimen reached the desired temperature. This temperature was then maintained by gradually reducing the power input until a stable setting was reached. Graphs of pyrometer readings versus time were constructed; and for repeatability, the technique was simply to reproduce the same furnace temperatures with time.

This procedure not only gave considerably decreased warm-up times but also had the advantage that closer control of specimen temperature was possible. It also reduces some of the doubt as to the validity of static calibrations; since with the machines running, practically identical furnace temperatures were obtained with the same power input versus time sequence.

Some variation was noticed if excessive oil was introduced into the bearings or if air drafts from neighboring machines were present. The drafts were largely eliminated by installing deflectors; and the other effects, including changes in room temperature, were readily compensated for by adjusting the power input to give the appropriate furnace temperature as required by the pyrometer reading versus time graph.

To avoid unnecessary vibrations once a test was begun, the machines were never stopped unless trouble developed. The load was simply removed or applied at the proper times, and the rest periods given until failure occurred. Transient vibrations during starting were best controlled by constraining the counterweights on the bearing housings and starting the machines at their nominal speed of 10,000 rpm. The speed was then adjusted to 5,000 rpm. All specimens that developed a visible transient vibration were discarded.

4. Calibration for Spanwise Temperature Distribution.

To determine the spanwise temperature distributions three thermocouples were placed at various stations along the specimen. Each thermocouple was positioned under a screw head; one at the center, one three-eighths of an inch from the center, and another on the opposite side at five-eighths of an inch from the center. Several furnaces were investigated in this respect, and the following average percentage variations from the temperature at the center were obtained:

Temp. °F.	3/8" Station	5/8" Station
150	2.0 °/o	3.5 °/o
300	4.5 °/o	7.0 °/o
450	6.5 °/o	9.0 °/o
600	8.0 °/o	11.5 °/o

As before, the calibration was done statically; and it is assumed that the distributions during operation would be similar. The results indicate a siz~~e~~able temperature gradient along the span of the specimen, but since almost all specimens failed very near the center this is not considered to be of primary importance.

IV. RESULTS AND DISCUSSION

The results of the fatigue tests are contained in Tables I through XIII. These tables give, for the different test phases, the number of cycles which the individual specimens sustained before failure. The computed values of the standard deviations and the means, $\overline{N}$ and $\overline{\log N}$, have been entered on the tables. A compilation of these values is given by Table XIV. After having been statistically evaluated, the data are presented in the form of frequency distributions (histograms) of log N by Figs. 7, 9, 11, and 12. For comparison, the Normal or Gaussian distribution is superimposed on each histogram.

Assuming the data to be logarithmic - normal (ref. 7); continuous frequency distributions of log N, derived from results of the uninterrupted tests at room temperature for S = 6,040 psi. and S = 6,800 psi, have been used to draw a statistically interpretable S - log N diagram for the material. The diagram is shown in Fig. 8. Data of incidental tests at various other stress levels have been indicated on the diagram by points. Under the same assumption of the data being logarithmic - normal, the Temperature - log N diagram in Fig. 10 was constructed.

In fatigue testing, one can probably never accumulate enough data. In the time available for this work an average of 18 specimens was tested in each phase, in the hope that at least the trends might be adequately uncovered. As far as possible all specimens of one series were tested with the same machine and furnace. When this was not done, the results were scrutinized for any variations between machines. On the basis of the results obtained, no deviations were detected.

Data of the continuous cycling tests show; that for rotary bending,

fatigue life does not attain a minimum within the range of test temperatures used. As given below, the average number of cycles to failure at the various temperatures were:

Temp. °F.	Room	150	300	450	600
$\overline{N}$x10^{-6} Cycles.	2.537	.868	.414	.173	.114

The continuous cycling results also indicate a minimum of scatter at the recrystallization temperature. On the basis of the number of specimens tested here, however; any correlation is not conclusive, and it is recommended that additional tests be conducted to substantiate this trend.

Recrystallization also seemed to have a bearing on fatigue life where rest periods were given. For specimens rested at 300°F, the data show an average fatigue life of 1.041x10^6 cycles compared to .663x10^6 cycles under continuous stress cycling at room temperature (an increase of 57 percnet). When rest periods at 150°F were given, the mean life was .919x10^6 cycles, an increase of 39 percent. For resting at 450°F, .826x10^6 cycles was the mean life, showing an increase of 25 percent.

Rest periods at room temperature after stressing at elevated temperature seemed to provide no beneficial effect, except when stress cycling was done at 150°F. The mean lives obtained are as shown in the following table.

Temp. °F.	150	300	450
$\overline{N}$x10^6 (Continuous cycling)	.868	.414	.173
$\overline{N}$x10^6 Rested at (room temperature)	1.013	.408	.175

The change in life at 150°F is an increase of 16.7 percent; while at the

other temperatures, the changes are negligible. Without further studies it cannot be safely inferred that recrystallization has any bearing here; that is, while an increase in life was obtained for stressing at a temperature less than recrystallization no changes were uncovered at recrystallization temperature and above.

Fig. 13 is a photograph of several specimens showing the characteristic types of failures obtained. Failure in shear was evidenced almost universally at each test temperature. The figure shows that at 300°F and higher, considerable surface damage was sustained before the resultant deformation was sufficient to stop the testing machine. The extent of this surface damage seems to be increasingly greater at the higher temperatures. A correlation with the temperature of recrystallization is, therefore, again illustrated.

V. CONCLUSIONS AND RECOMMENDATIONS

From the results obtained in this investigation, the following conclusions are made:

1. For continuous stress cycling in rotary bending the material did not exhibit a minimum in fatigue life within the range of test temperatures used.

2. Room temperature resting after stressing at 150°F increased the fatigue life about 17 percent, whereas no appreciable increase or decrease in life was obtained by resting at room temperature from stressing at 300 or 450°F.

3. With rest periods given at 150°F the mean fatigue life was increased 39 percent over the mean life under continuous cycling at room temperature. When rest periods were given at 300°F the increase was 57 percent, and for 450°F the increase was 25 percent. Maximum benefit was thus achieved by resting the specimens near the recrystallization temperature.

4. The temperature of recrystallization also seemed to be related to the amount of scatter in the results. As measured by the standard deviations in cycles, the scatter for continuous cycling was definitely a minimum at recrystallization temperature.

The following recommendations for further test programs are made:

1. A similar investigation to this should be conducted at intermediate temperatures to substantiate the effects of recrystallization. In this respect, metallographic studies should be made at various times during the testing to determine if recrystallization was actually occurring

and to what extent. Several temperatures near recrystallization should be investigated so that the effects of stress history and temperature on the phenomenon of recrystallization might be more fully understood.

2. A project in itself would be a more thorough statistical investigation of variations in scatter at different temperatures, with perhaps 50 or 60 specimens being run at each temperature.

3. Extensions to similar tests at different levels of stress, and to the effects of rest periods of various durations are obviously desirable.

4. Investigations of this nature should be carried out on the more commonly used commercial aluminum alloys to see if a similar behavior could be predicted.

Towards further improvement in the furnaces used in this investigation it is recommended that:

1. Stainless steel reflectors be installed between the heating coils and the furnace walls.

2. The terminals be enlarged so that the junctions to the coils would not become over heated.

For the test arrangement in general it is suggested that the individual fatigue machines be isolated from one another to eliminate any carry over of vibrations.

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TABLE I

S-N Data, Room temperature.

Specimen Number	Applied Load lb	S Stress	N No. of Cycles $x10^{-3}$	log N
1	10.5	7,930	192	5.283
2	10.2	7,700	330	5.619
3	10.0	7,550	363	5.560
4	9.5	7,170	619	5.792
5	9.0	6,800	985	5.993
6	8.5	6,420	1,120	6.049
7	8.0	6,040	1,511	6.179
8	7.8	5,890	1,746	6.242
9	7.7	5,810	4,014	6.604
10	7.5	5,660	3,950	6.597
11	7.0	5,280	6,958	6.842
12	6.0	4,530	18,675*	7.271
13	5.0	3,775	47,437*	7.676
14	2.0	1,510	54,069*	7.733

* Removed before failure.

TABLE II

Number of cycles to failure. S = 6,040 psi.
Continuous cycling at T = Room.

Specimen Number	N No. of Cycles $\times 10^{-3}$	log N	Specimen Number	N No. of Cycles $\times 10^{-3}$	log N
1	1,150	6.061	12	2,795	6.446
2	1,208	6.082	13	2,894	6.461
3	1,334	6.125	14	2,989	6.476
4	1,403	6.147	15	3,058	6.485
5	1,504	5.177	16	3,059	6.486
6	1,511	6.179	17	3,186	6.503
7	1,552	6.191	18	3,406	6.532
8	1,631	6.212	19	3,657	6.563
9	1,714	6.234	20	3,666	6.564
10	1,844	6.266	21	4,021	6.604
11	1,940	6.288	22	6,291	6.799

$\overline{N}$ = 2,537,000 cycles; σ = 1,220,000 cycles.

$\overline{\log N}$ = 6.358; σ = 0.198

TABLE III

Number of cycles to failure. S = 6,040 psi.
Continuous cycling at T = 150°F.

Specimen Number	N No. of Cycles $x10^{-3}$	log N	Specimen Number	N No. of Cycles $x10^{-3}$	log N
1	259	5.413	17	836	5.922
2	357	5.553	18	855	5.932
3	370	5.568	19	862	5.936
4	505	5.703	20	870	5.940
5	507	5.705	21	912	5.960
6	569	5.755	22	942	5.974
7	602	5.780	23	1,000	6.000
8	603	5.780	24	1,096	6.040
9	651	5.814	25	1,122	6.050
10	660	5.820	26	1,172	6.069
11	663	5.822	27	1,217	6.085
12	687	5.837	28	1,237	6.092
13	754	5.877	29	1,280	6.107
14	777	5.890	30	1,382	6.141
15	798	5.902	31	1,633	6.213
16	809	5.908	32	1,807	6.257

$\overline{N}$ = 868,000 cycles; σ = 352,000 cycles.

$\overline{\log N}$ = 5.901; σ = 0.186

TABLE IV

Number of cycles to failure. S = 6,040 psi.
Continuous cycling at T = 300°F.

Specimen Number	N No. of Cycles $x10^{-3}$	log N
1	268	5.428
2	301	5.479
3	306	5.486
4	337	5.528
5	352	5.547
6	353	5.548
7	416	5.619
8	433	5.636
9	435	5.638
10	468	5.670
11	478	5.679
12	485	5.686
13	494	5.694
14	497	5.696
15	584	5.766

$\overline{N}$ = 414,000 cycles; σ = 87,300 cycles.

$\overline{\log N}$ = 5.607; σ = 0.095

TABLE V

Number of cycles to failure. S = 6,040 psi.
Continuous cycling at T = 450°F.

Specimen Number	N No. of Cycles $x10^{-3}$	log N	Specimen Number	N No. of Cycles $x10^{-3}$	log N
1	98	4.991	10	187	5.272
2	99	4.996	11	197	5.294
3	118	5.072	12	204	5.310
4	128	5.107	13	205	5.312
5	147	5.167	14	205	5.312
6	152	5.182	15	207	5.316
7	157	5.196	16	215	5.332
8	167	5.223	17	222	5.346
9	176	5.246	18	224	5.350

$\overline{N}$ = 173,000 cycles; σ = 40,400 cycles.

$\overline{\log N}$ = 5.224; σ = 0.113

TABLE VI

Number of cycles to failure. S = 6,040 psi.
Continuous cycling at T = 600°F.

Specimen Number	N No. of Cycles $x10^{-3}$	log N
1	39	4.591
2	54	4.732
3	90	4.954
4	90	4.954
5	94	4.973
6	96	4.982
7	101	5.004
8	133	5.124
9	159	5.201
10	161	5.207
11	166	5.220
12	189	5.276

$\overline{N}$ = 114,000 cycles; σ = 45,000 cycles.

$\overline{\log N}$ = 5.018; σ = 0.196

TABLE VII

Number of cycles to failure. S = 6,040 psi.
Stressed at T = 150°F. Rested at T = Room.

Specimen Number	N No. of Cycles $x10^{-3}$	log N
1	526	5.721
2	569	5.755
3	605	5.782
4	889	5.949
5	952	5.979
6	1,029	6.012
7	1,035	6.015
8	1,083	6.035
9	1,086	6.036
10	1,136	6.055
11	1,157	6.063
12	1,230	6.090
13	1,271	6.104
14	1,291	6.111
15	1,343	6.128

$\overline{N}$ = 1,013,000 cycles; σ = 254,000 cycles.

$\overline{\log N}$ = 5.989; σ = 0.128

TABLE VIII

Number of cycles to failure. $S = 6,040$ psi.
Stressed at $T = 300^{\circ}F$. Rested at T = Room.

Specimen Number	N No. of Cycles $x10^{-3}$	log N
1	148	5.170
2	244	5.387
3	266	5.425
4	275	5.439
5	322	5.508
6	322	5.508
7	345	5.538
8	348	5.542
9	377	5.576
10	401	5.603
11	557	5.764
12	558	5.747
13	563	5.751
14	590	5.771
15	804	5.905

$\overline{N} = 408,000$ cycles; $\sigma = 166,000$ cycles.

$\overline{\log N} = 5.574$; $\sigma = 0.181$

TABLE IX

Number of cycles to failure. $S = 6,040$ psi.
Stressed at $T = 450^\circ$F. Rested at T = Room.

Specimen Number	N No. of Cycles $x10^{-3}$	log N
1	112	5.049
2	118	5.072
3	135	5.130
4	138	5.140
5	142	5.152
6	147	5.167
7	149	5.173
8	173	5.238
9	173	5.238
10	196	5.292
11	203	5.307
12	208	5.318
13	237	5.375
14	244	5.387
15	255	5.407

$\overline{N} = 175,000$ cycles; $\sigma = 44,800$ cycles.

$\overline{\log N} = 5.230$; $\sigma = 0.111$

TABLE X

Number of cycles to failure. S = 6,800 psi.
Continuous cycling at T = Room.

Specimen Number	N No. of Cycles x10^{-3}	log N	Specimen Number	N No. of Cycles x10^{-3}	log N
1	381	5.581	12	646	5.810
2	399	5.601	13	676	5.830
3	403	5.605	14	714	5.854
4	404	5.606	15	780	5.892
5	437	5.640	16	788	5.897
6	446	5.649	17	877	5.943
7	481	5.682	18	927	5.967
8	491	5.691	19	943	5.975
9	577	5.761	20	970	5.987
10	613	5.787	21	985	5.993
11	619	5.792	22	1,025	6.011

$\overline{N}$ = 663,000 cycles; σ = 214,000 cycles.

$\overline{\log N}$ = 5.798; σ = 0.144

TABLE XI

Number of cycles to failure. $S = 6,800$ psi.
Stressed at T = Room. Rested at $T = 150^{\circ}F$.

Specimen Number	N No. of Cycles $\times 10^{-3}$	log N
1	486	5.687
2	549	5.740
3	597	5.823
4	665	5.823
5	745	5.872
6	749	5.874
7	758	5.880
8	854	5.931
9	974	5.989
10	977	5.990
11	999	6.000
12	1,129	6.053
13	1,303	6.115
14	1,416	6.151
15	1,580	6.199

$\overline{N}$ = 919,000 cycles; σ = 313,000 cycles.

$\overline{\log N}$ = 5.939; σ = 0.146

TABLE XII

Number of cycles to failure. S = 6,800 psi.
Stressed at T = Room. Rested at T = 300°F.

Specimen Number	N No. of Cycles $\times 10^{-3}$	log N
1	345	5.538
2	464	5.667
3	467	5.669
4	476	5.678
5	770	5.886
6	896	5.952
7	962	5.983
8	1,026	6.011
9	1,050	6.021
10	1,064	6.027
11	1,111	6.046
12	1,179	6.072
13	1,405	6.148
14	1,785	6.252
15	1,821	6.260
16	1,836	6.264

$\overline{N}$ = 1,041,000 cycles; σ = 472,000 cycles.

$\overline{\log N}$ = 5.967; σ = 0.219

TABLE XIII

Number of cycles to failure. S = 6,800 psi.
Stressed at T = Room. Rested at T = 450°F.

Specimen Number	N No. of Cycles $x10^{-3}$	log N
1	436	5.639
2	448	5.651
3	450	5.653
4	463	5.666
5	484	5.685
6	633	5.801
7	636	5.803
8	651	5.814
9	695	5.842
10	733	5.866
11	872	5.940
12	910	5.959
13	954	5.980
14	984	5.993
15	1,048	6.020
16	1,192	6.076
17	2,447	6.389

$\overline{N}$ = 826,000 cycles; σ = 465,000 cycles.

$\overline{\log N}$ = 5.869; σ = 0.189

TABLE XIV

Compilation of standard deviations and means.

Stress History	No. of Spec.	$\overline{N} \times 10^{-6}$ Cycles	$\sigma_N \times 10^{-6}$	$\overline{\log N}$	$\sigma_{\log N}$
Continuous Cycling T=72°F., S=6,040 psi.	22	2.537	1.220	6.358	0.198
Continuous Cycling T=150°F., S=6,040 psi.	32	0.868	0.352	5.901	0.186
Continuous Cycling T=300°F., S=6,040 psi.	15	0.414	0.087	5.607	0.095
Continuous Cycling T=600°F., S=6,040 psi.	18	0.173	0.040	5.224	0.113
Continuous Cycling T=600°F., S=6,040 psi.	12	0.114	0.045	5.018	0.196
Stressed at T=150°F. Rested at T=72°F. S=6,040 psi.	15	1.013	0.254	5.989	0.128
Stressed at T=300°F. Rested at T=72°F. S=6,040 psi.	15	0.408	0.166	5.574	0.181
Stressed at T=450°F. Rested at T=72°F. S=6,040 psi.	15	0.175	0.045	5.230	0.111
Continuous Cycling T=72°F., S=6,800 psi.	22	0.663	0.214	5.798	0.144
Stressed at T=72°F. Rested at T=150°F. S=6,800 psi.	15	0.919	0.313	5.939	0.146
Stressed at T=72°F. Rested at T=300°F. S=6,800 psi.	16	1.041	0.472	5.967	0.219
Stressed at T=72°F. Rested at T=450°F. S=6,800 psi.	17	0.826	0.465	5.869	0.189

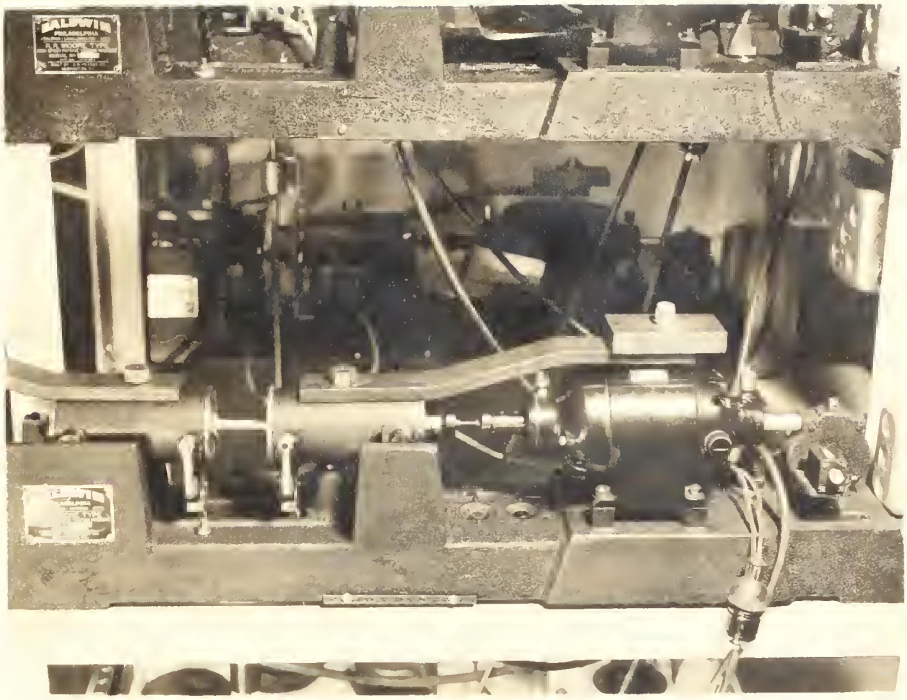


Fig. 1 R. R. Moore fatigue testing machine. (Note counterweights)

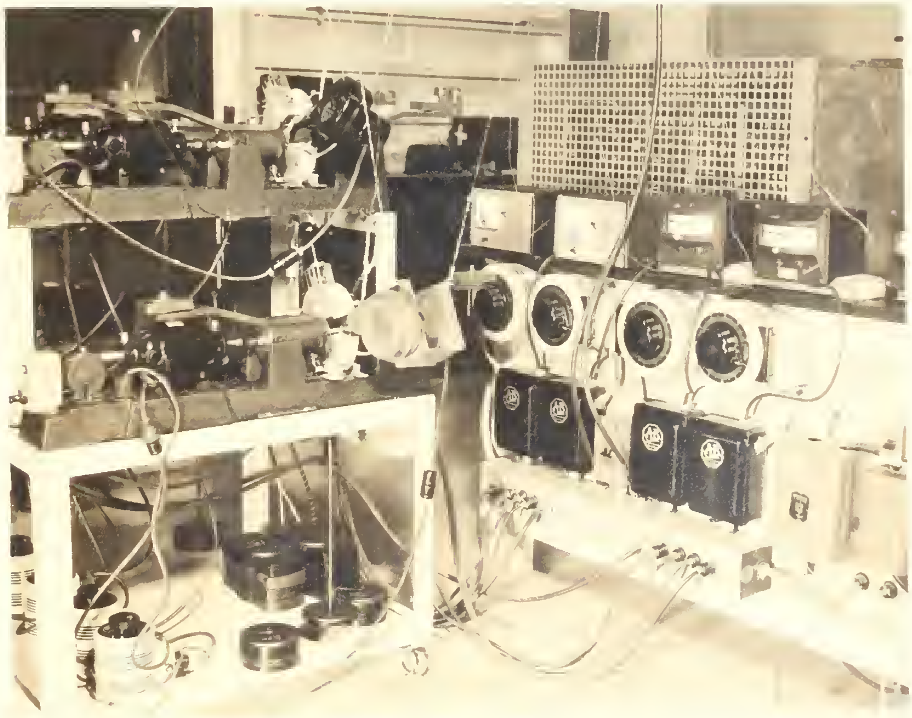
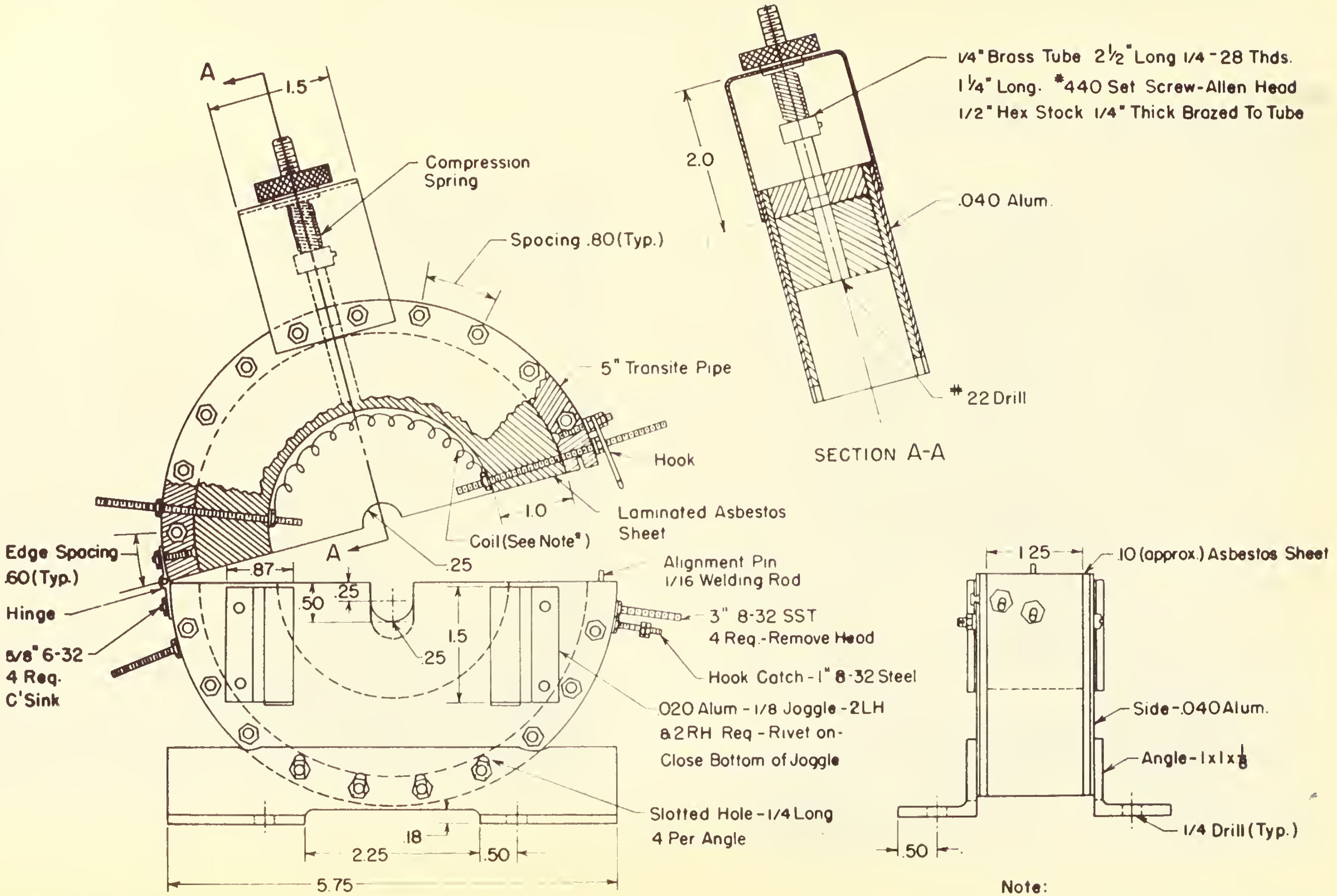


Fig. 2 General view of furnace control equipment and machines. (Note fans for cooling specimens).



Note:

1. *Coil - 48" No. 15 Tophet-A wound into flat coil - 1.10 wide x .20 (approx.) deep.
2. All dimensions inches

FIG. 3 - FURNACE FOR R.R. MOORE FATIGUE TESTING MACHINE

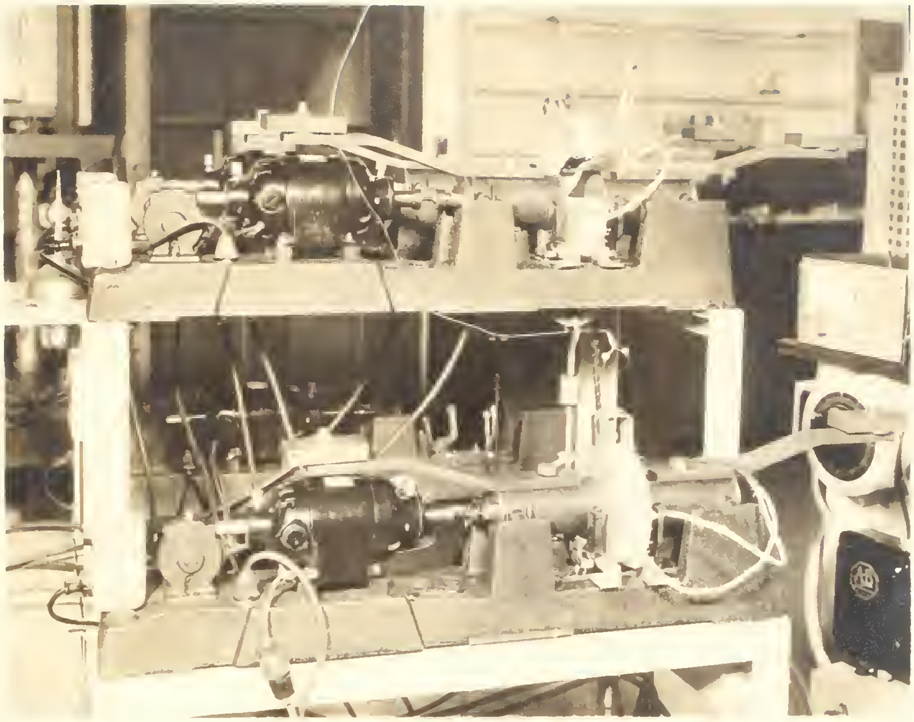


Fig. 4 R. R. Moore machines with furnaces installed.

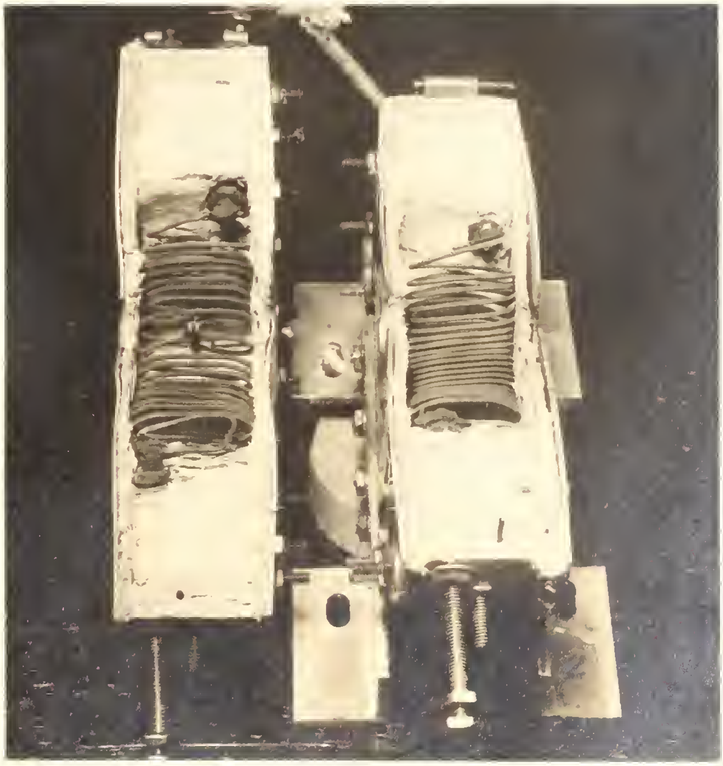
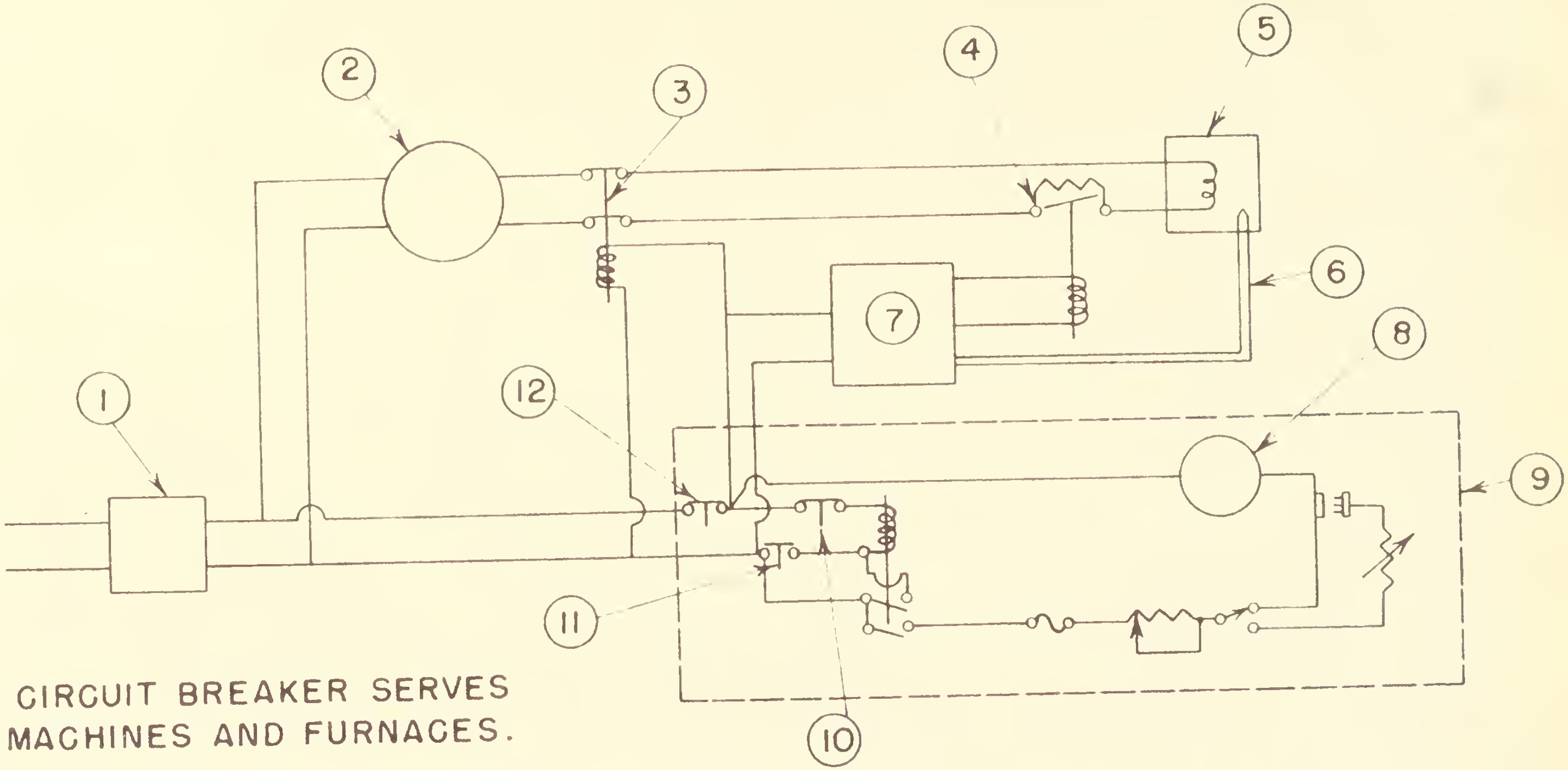


Fig. 5 Closeup of furnace interior.



NOTE:
EACH CIRCUIT BREAKER SERVES
TWO MACHINES AND FURNACES.

① CIRCUIT BREAKER
② POWERSTAT
③ FURNACE CUT-OFF RELAY
④ FURNACE CUT-OFF RELAY
AND BALLAST RESISTOR
⑤ FURNACE
⑥ THERMOCOUPLE
⑦ PYROMETER
⑧ MOTOR
⑨ R.R.MOORE MACHINE
⑩ STOP SWITCH
⑪ START SWITCH
⑫ SPECIMEN FAILURE CUT-OFF SWITCH

FIG. 6

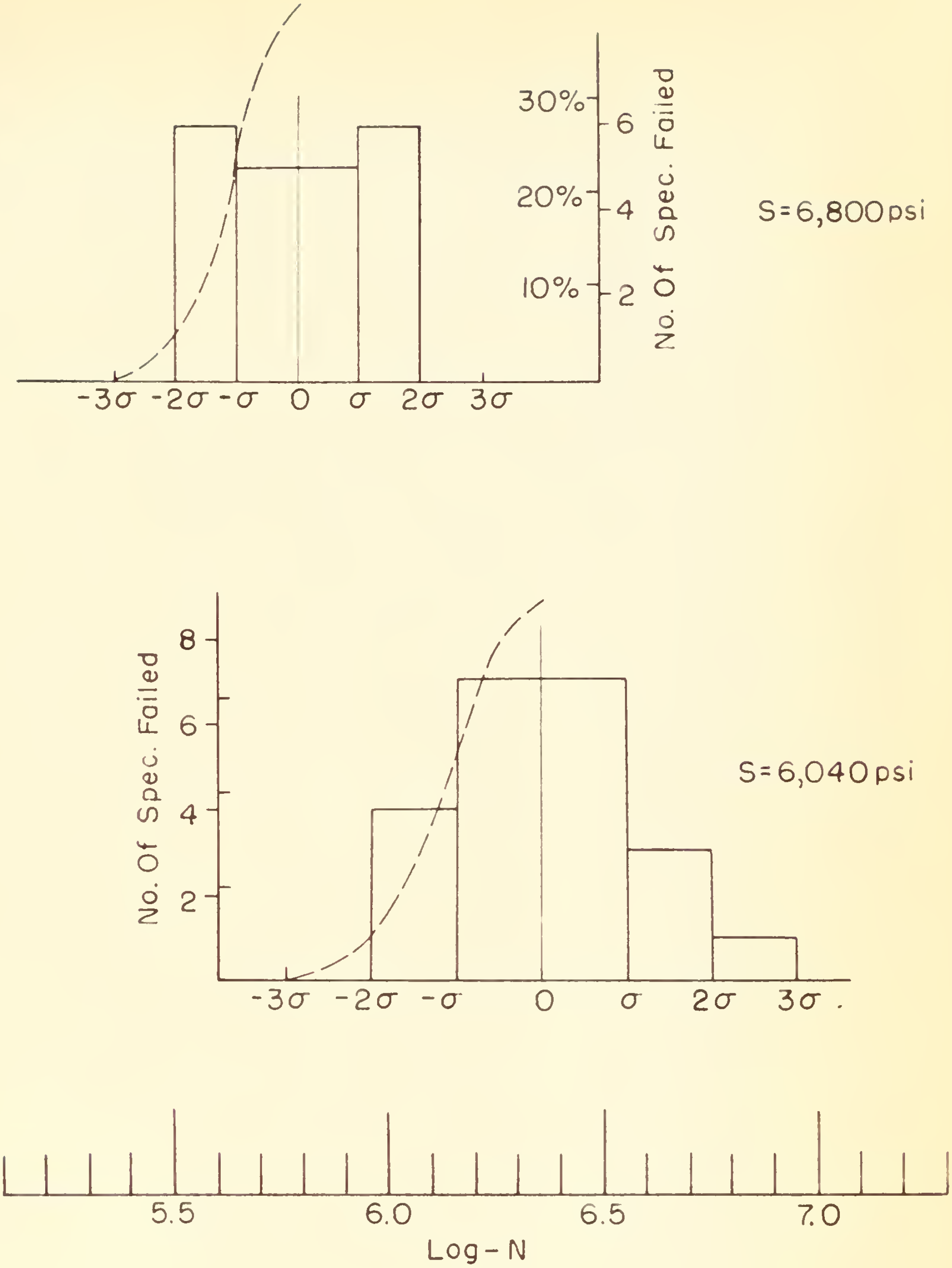


FIG. 7 — COMPARISON OF FATIGUE LIFE UNDER CONTINUOUS CYCLING AT ROOM TEMPERATURE

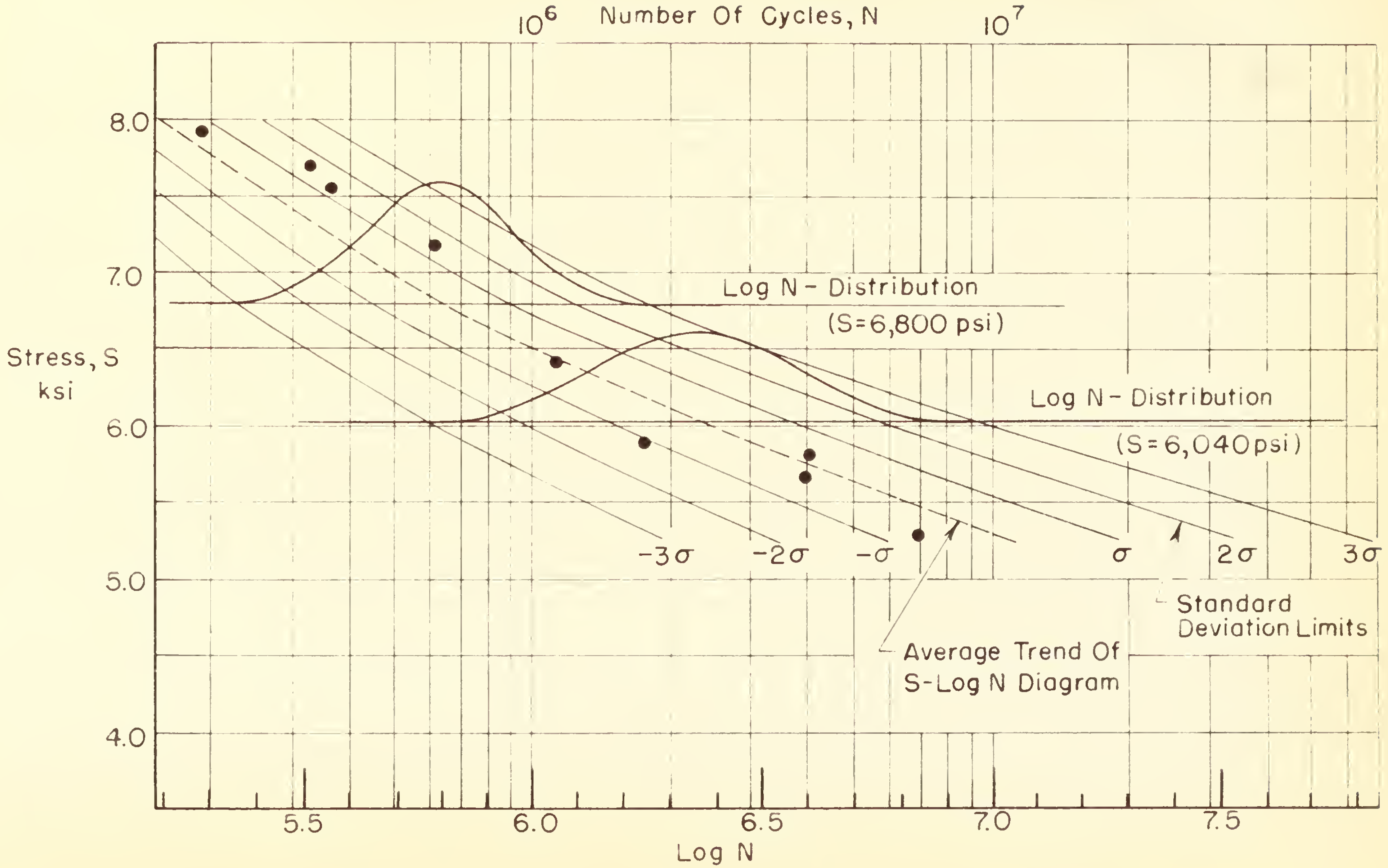


FIG. 8 – STRESS-LOG N DIAGRAM – CONTINUOUS CYCLING AT ROOM TEMPERATURE

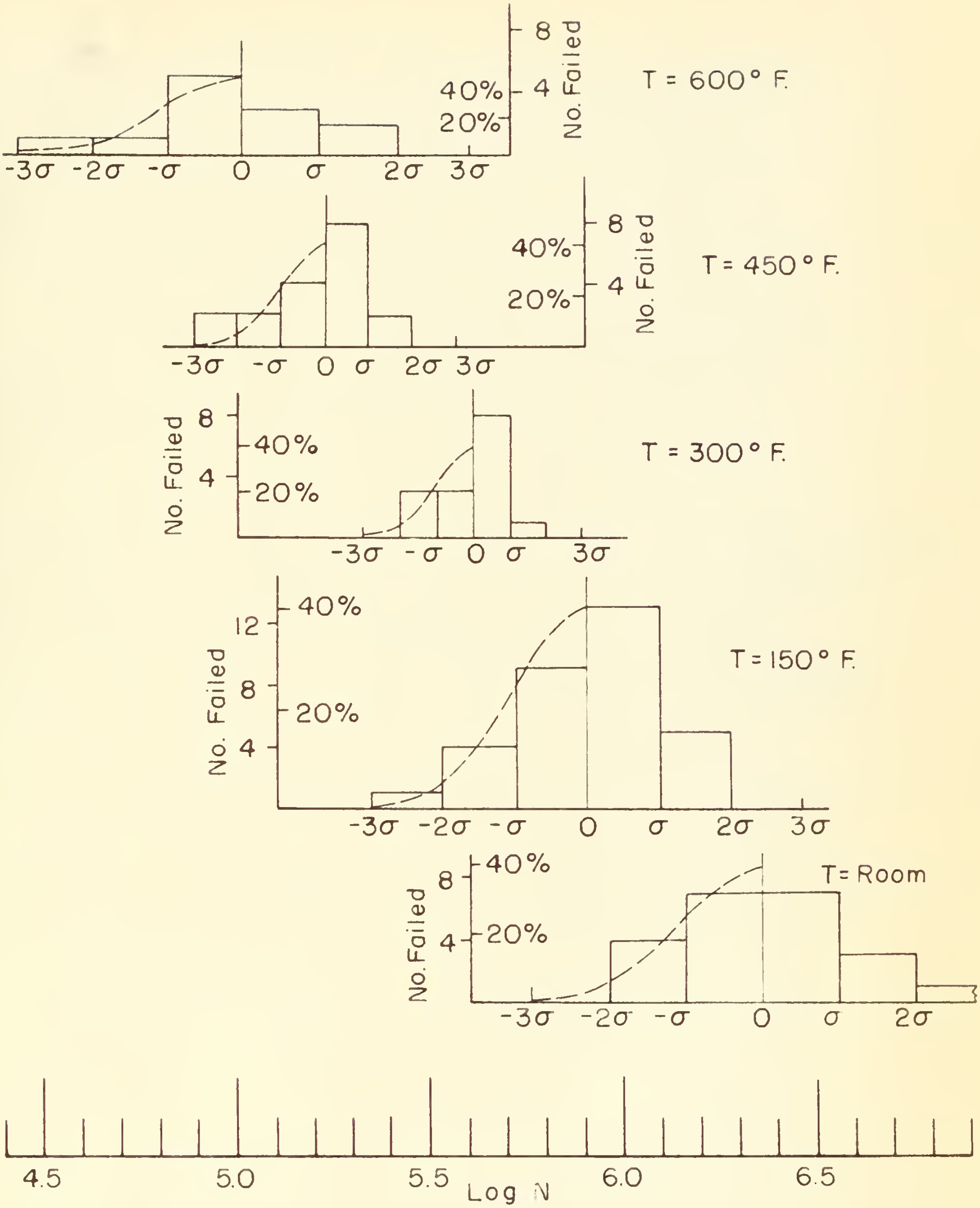


FIG. 9 - COMPARISON OF FATIGUE LIFE UNDER CONTINUOUS CYCLING AT S = 6,040 PSI

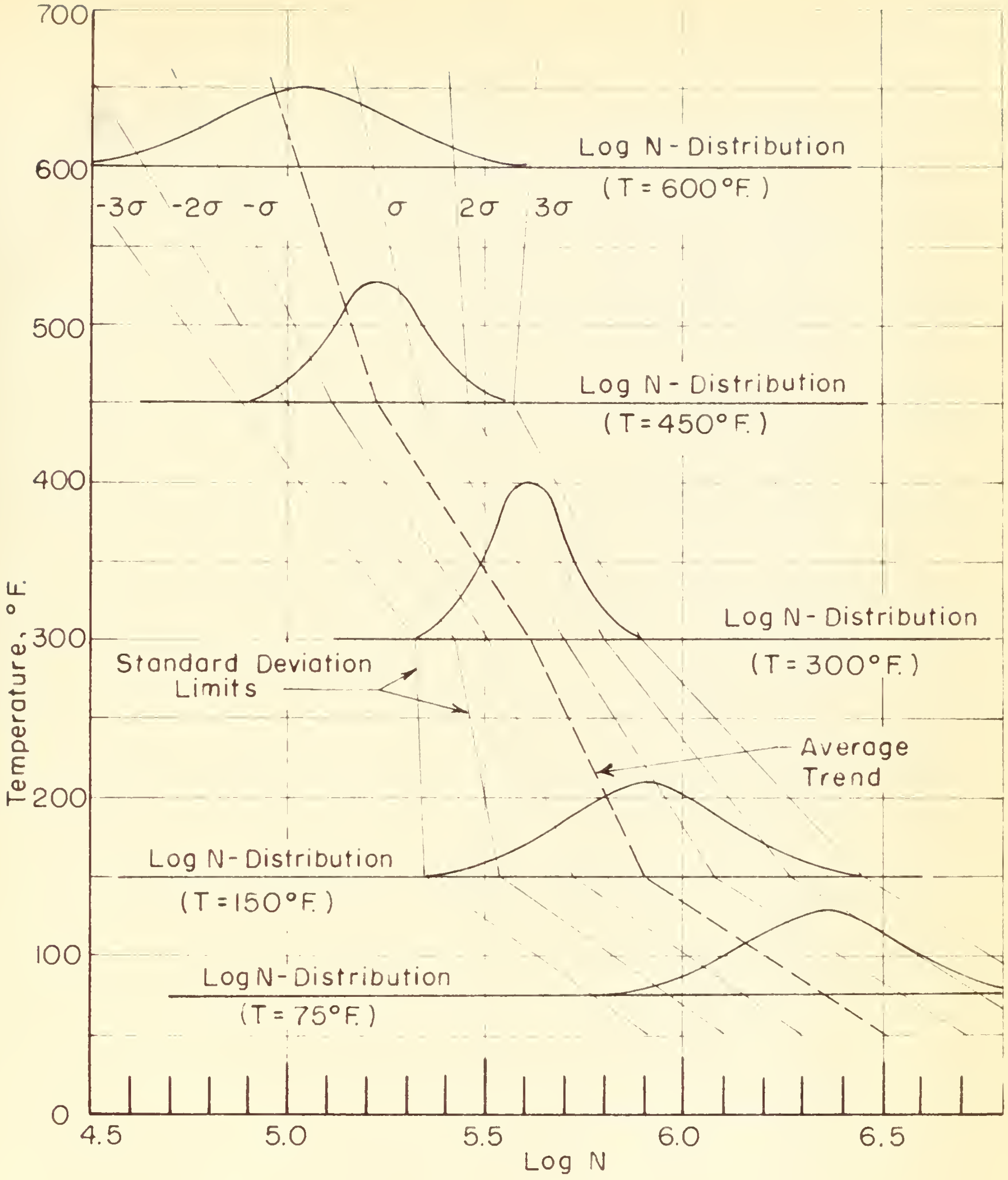


FIG. 10 – TEMPERATURE – LOG N DIAGRAM FOR CONTINUOUS CYCLING AT S = 6,040 PSI

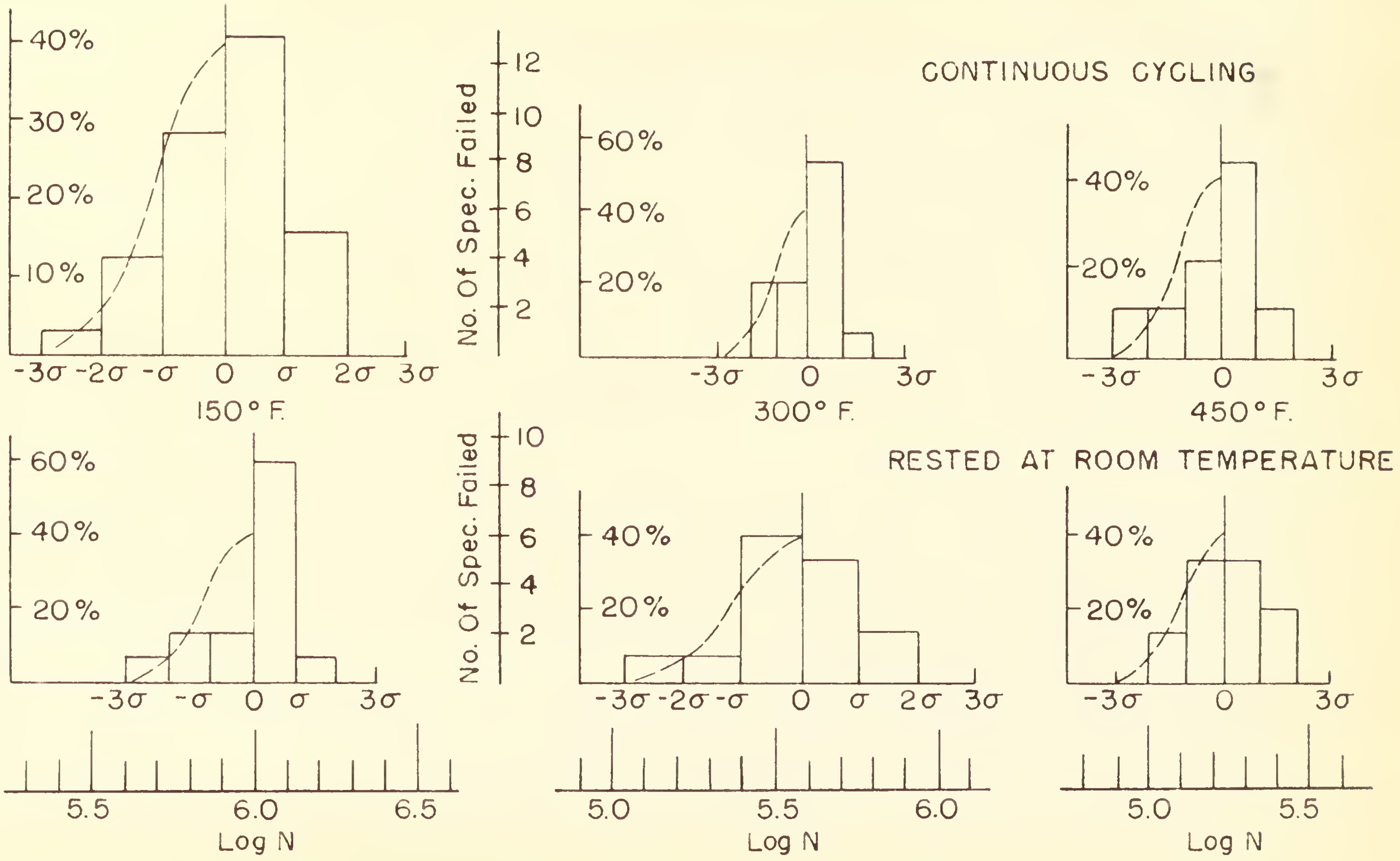


FIG. 11 – COMPARISONS OF FATIGUE LIFE UNDER CYCLING AT 150° F., 300° F., AND 450° F. WITH REST PERIODS AT ROOM TEMPERATURE TO FATIGUE LIFE UNDER CONTINUOUS CYCLING AT 150° F., 300° F., AND 450° F. S = 6,040 PSI

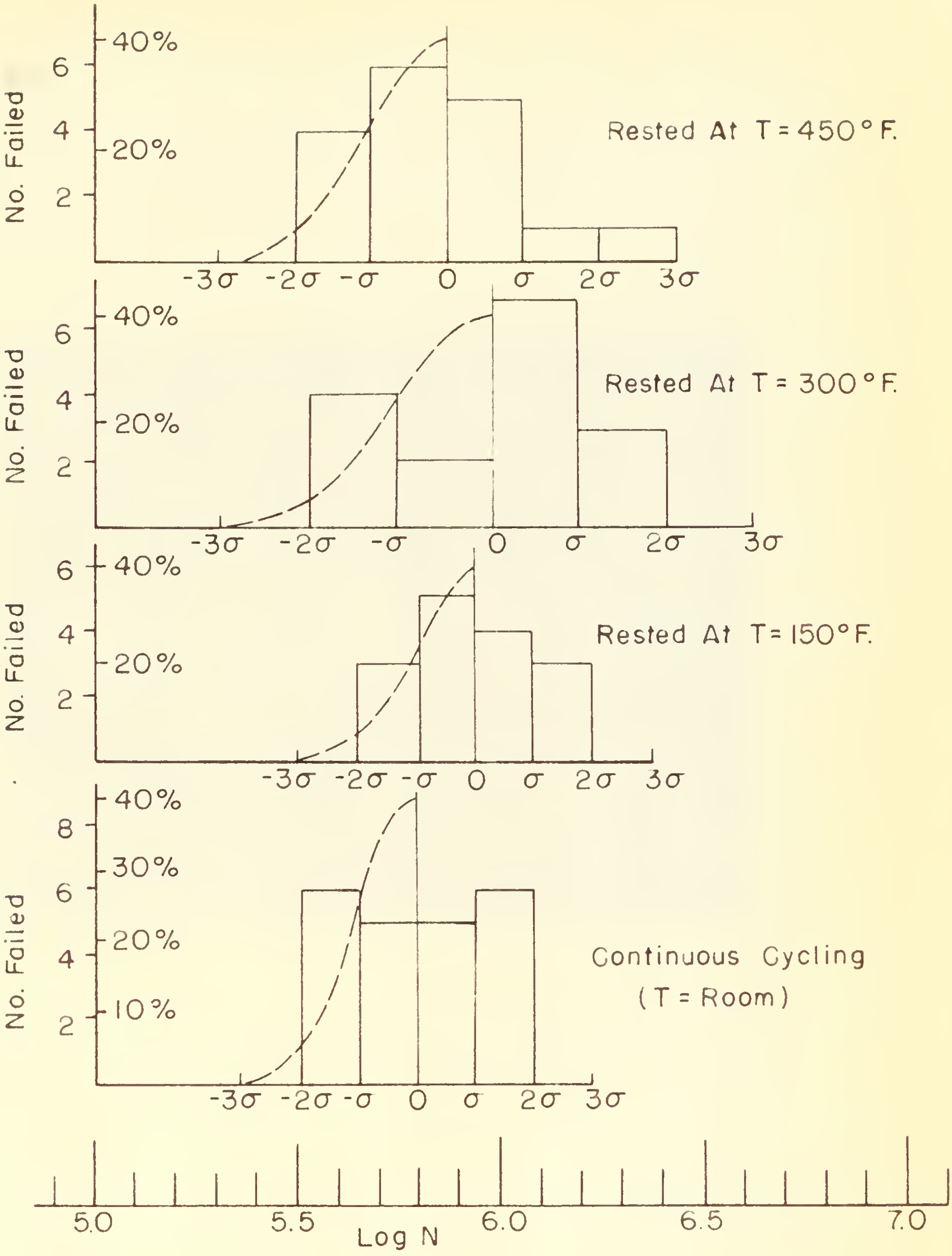


FIG. 12 - COMPARISONS OF FATIGUE LIFE UNDER CYCLING AT ROOM TEMPERATURE WITH REST PERIODS AT 150°F, 300°F., AND 450°F. TO FATIGUE LIFE UNDER CONTINUOUS CYCLING AT ROOM TEMPERATURE. S = 6,800 PSI

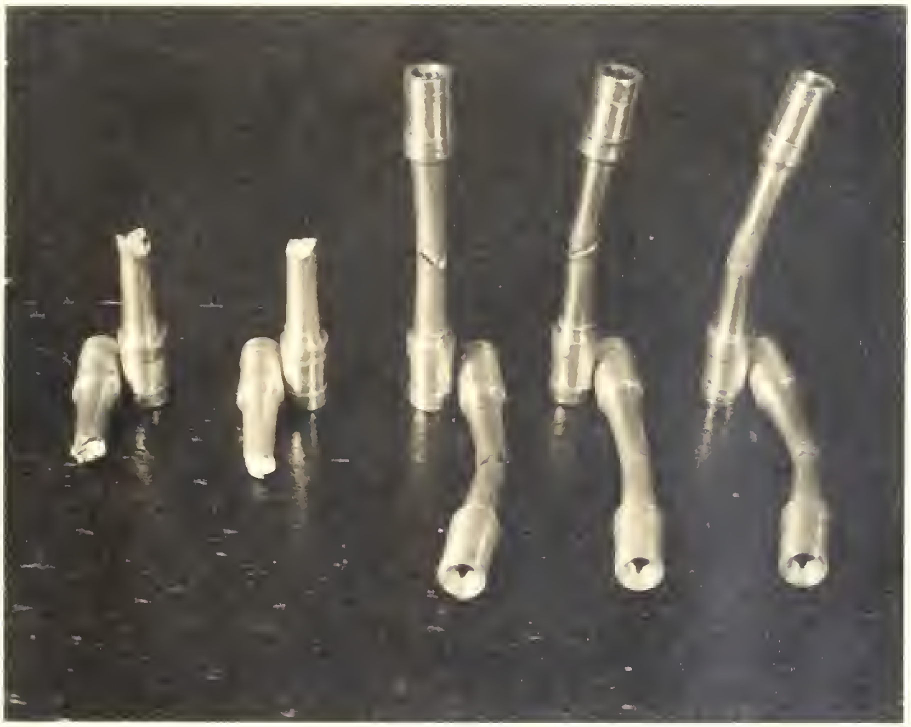


Fig. 13 Test specimens showing typical failures.

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Thesis
B457

Berry
Fatigue of aluminum as affected by temperature and intermittent periods of rest.